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Relationships Between Auditory Brainstem Responses & Timed-Sentence Comprehension

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Introduction

Language comprehension is a complex process involved in every facet of daily life, including particular aspects such as interpreting meanings of sentences and auditory processing of those sentences. Various brain structures in sentence comprehension work together to complete such a task accurately and efficiently. Most existing literature focuses on the roles of cortical structures in the frontal and temporal lobes in language processing (Friederici, 2002; Mack et al., 2013; Rogalsky et al., 2015). The parts of the brain that are less understood, in relation to sentence comprehension, involve the brainstem; however, the brainstem has recently been demonstrated to be a subcortical feature that influences auditory language processing (Skoe et al., 2011; Skoe et al., 2015; Skoe et al., 2017). The current study was conducted to observe auditory brainstorm response (ABR) in adults, as well as their understanding of sentences, so as to assess the possible relationships between subcortical structures and timed-sentence comprehension.

Sentence Processing in Adults

Sentence processing is an important aspect of language comprehension because of the role it plays in effectively communicating in our day-to-day lives. Understanding sentences is a skill that is built upon the comprehension of smaller units of language, starting with sounds and words, then progressing to the ability to interpret and make meaning of syntax. Fallon, Peelle, and Wingfield (2006) assessed the automatic process of rapidly decoding acoustic patterns along with meaning to interpret speech. Their study focused on differences in adults’ comprehension of sentences that vary in complexity. When presented with quasi-randomized sentences of various types—active-conjoined sentences, subject-relative sentences, and object-relative sentences—at different rates (see Table 1), participants either responded to true-false questions or recalled the sentence to indicate comprehension.

Fallon et al. (2006) found that both young (17-23 years old) and older (67-83 years old) adults demonstrated longer pauses at clause boundaries, reflecting increased complexity of object- and subject-relative sentences compared to active-conjoined sentences. Specifically, individuals demonstrated longer pause durations after hearing more complex sentences before responding to recall or true/false questions; the greatest durations occurred for object-relative sentences, meaning they had slower reaction times before responding.

The current study employs many of these methods, including active-conjoined, object-relative, and subject-relative sentence types, as well as the timed-presentation of pseudorandomized stimuli.

Neural Involvement in Spoken Sentence Processing

Most research regarding the neural correlates of sentence processing—and language comprehension as a whole—has revolved around the contributions of cortical structures. Particularly during auditory sentence processing, syntactic information is combined with both semantic and phonological information; neurologically, then, auditory language comprehension involves the processes of a bilateral temporo-frontal network in the human cortex (Friederici, 2002). The role of Broca's area, located in the frontal lobe, in language has been a well-studied topic of neurological research. A specific area of study regarding this part of the brain revolves around Broca's aphasia, in which damage to the region impairs language production, and typically also involves difficulty comprehending complex sentences (Mack et al., 2013). Additionally, deficits in complex sentence processing results from damage to the anterior or posterior Perisylvian regions, which consists of the Sylvian fissure (lateral sulcus), Wernicke's area, and Broca's area of the left hemisphere (Mack et al., 2013). A labelled diagram of these regions can be seen in Figure 1 (Pinel, 2000).

Because previous literature has established this region as important for language processing, this information is used to correlate sentence comprehension and cortical activity in adults. For example, Mack and colleagues (2013) investigated how adults (two groups: ages 19-38 and 54-70) processed complex sentences using a sentence-to-picture matching task to measure accuracy and reaction time, as well as MRI results to correlate passive sentence comprehension to cortical activity in adults. Twenty different verbs were included in four sentences each, two of which were active sentences (e.g. verb: chase—*the boy was chasing the girl; the girl was chasing the boy)* and two that were passive sentences (e.g. verb: chase—*the boy was chased by the girl; the girl was chased by the boy)*. Mack et al. (2013) found that passive sentence comprehension was associated with activation of the inferior frontal gyrus and the left posterior temporo-occipital regions.

Rogalsky and colleagues (2015) also assessed Broca's area's contribution to sentence comprehension by comparing sentences that involved different kinds of syntactic movement. fMRI was used to record the neural activity in participants ranging from 18 to 29 years who heard sentences that were either structured/grammatical (e.g. *The boy was chased by the girl*) or ungrammatical/scrambled (e.g. *Chased girl the was boy the by*). Additional test stimuli varied in wh-movement: short control, short movement, long control, and long movement; "Short movement" sentences involved shorter distance of moving the wh-word within the sentence from the original position in the control example compared to "long movement" sentences (2015).

Rogalsky et al. (2015) reported that Broca's area was activated more when participants heard long-movement sentences than when they heard short-movement sentences; the researchers conjectured this was because long-movement sentences represent greater complexity, with two clauses instead of one, and greater movement distance (see Table 2). There was also more activation in Broca's area when participants listened to structured sentences than when they listened to unstructured sentences; thus, this research points to Broca's area as an important cortical site for processing syntax and extracting the meanings of 'real' English sentences.

The existing literature regarding auditory sentence processing has primarily looked at the functions of cortical structures. However, the auditory processing system is made up of both the cortex and subcortical structures such as the brainstem. That is, there are steps that auditory signals need to go through prior to reaching the cortex, and so it is equally beneficial to know how subcortical structures influence auditory language comprehension, potentially answering questions left unanswered by cortical studies.

Subcortical Processing of Language

Subcortical structures such as the brainstem are the first to interact with auditory signals that initiate the process of comprehending verbal language (see Figure 2; Pujol & Irving, 2016). Auditory brainstem responses (ABRs) are neurophysiological displays of subcortical auditory processing, typically recorded in response to one-syllable sounds such as /da/ (Skoe et al., 2017). The timing of an ABR corresponds to the onset and offset of that stimulus, as well as the duration of the response, with peaks relates to acoustic landmarks in the stimulus; each peak occurs about 6-8 ms after the corresponding landmark, which is equivalent to the time taken for the signal to travel from the cochlea to the rostral brainstem (Skoe et al., 2015). The five waves of a response are produced in specific parts of the brainstem, with the first wave originating from the distal portion of the cochlear nerve and the fifth wave in the lateral lemniscus in the pons (see

Figure 3; Banoub et al., 2003). A strength of recording the ABR is the fact that it is so site specific, allowing us to pinpoint exact regions within the brainstem where activity occurs.

A few studies have demonstrated an association between ABR and language. Skoe and colleagues (2017) studied the reading ability study of adults (ages 18-30 years), comparing this to variability in their Wave V latencies. Whereas previous researchers had found that faster (shorter) ABR latencies were associated with better reading skills in children (Banai et al., 2009), Skoe et al. (2017) found that slower (longer) latencies indicated more mature reading skills in adults (Skoe et al., 2017). That is, participants with Wave V latencies that fell below the normative range (Skoe et al., 2015) had lower reading scores compared to those with latencies above normative range. Such evidence of connections between ABR and reading, which draws heavily on underlying language knowledge, indicates that there is a potential for the brainstem to be involved in the process of understanding syntax. While latency is a good candidate to correlate with sentence comprehension measures, it will not be incorporated in the current study due to technical considerations; measures that will be considered are stability and specificity.

Stability. Evidence for relationships between ABR and spoken language have just emerged recently. Tecoulesco, Skoe & Naigles (in press; Tecoulesco, 2018) explored the ABR latency and stability measures as potential predictors of syntactic, semantic, and phonological performance in typically developing (TD) children and children with Autism Spectrum Disorder (ASD). Stability refers to how consistently an individual processes the same sound the same way every time they hear it; that is, it is an indication of whether the neurons fire in sync in response to the same sound every time it is heard. Greater stability means the brainstem pattern of activation is similar across two separate waves of data collection. In this study, children aged 7 to 17 were visited at home and their ABRs were recorded. They also heard eighty pairs of novel bisyllabic words as the phonological task stimuli: forty identical (e.g. *kulkeet* and *kulkeet*) and forty differed by one sound (e.g. *kulkeet* and *tulkeet*). To measure syntactic ability, two subsets of the Clinical Evaluation of Language Fundamentals were used: Repeating Sentences, which tests how well the participants can recall and repeat sentences of varying complexity, and Formulating Sentences, which assesses the extent to which participants can verbally form syntactically correct sentences that vary in complexity.

In both TD and ASD participants, those with greater /da/ stability demonstrated better phonological discrimination and better syntactic performance (Tecoulesco, et al., in press). Wave V latency did not yield significant correlations with either language measure. In sum, the brainstem was shown in this study to play a role in complex language function and the ability to process language. Methodologically, this study also demonstrated that ABR measures such as /da/ stability can illuminate individual differences.

Specificity. Another measure of the ABR is specificity—the differentiation between different auditory stimuli, with greater specificity indicating greater ability to discrimination between to different sounds, such as /ba/ and /ga/. Specificity can be examined at the group level using the cross-phaseogram developed in MATLAB by Skoe, Nicol, and Kraus (2011), who assessed the ABRs of 90 children ages 8 to 13 years recorded in response to /ba/ and /ga/ stimuli. The first part of /ga/ (2480 Hz) differs from the first part of /ba/ (900 Hz) in that it has a higher frequency. Higher frequencies result in faster ABR peak latencies—meaning peaks occur earlier—than lower frequencies, thus the /ga/ phase is expected to lead the /ba/ phase (see Figure 4); this may be attributed to the structure of the cochlea: higher frequencies are processed at the base while lower frequencies are processed further along toward the apex (Dobie & Van Hemel, 2004).

Visual representation of this difference in wave phases is observed in the color patterns of the cross-phaseogram (see Figure 5). The pattern that is expected is red during the initial 50 milliseconds of the 170 millisecond stimuli where the /ga/ phase leads the /ba/ phase, indicative of greater distinction between the two sounds. The later portion of time would be expected to appear green in color as the /ah/ ending of the sounds is the same and thus the phases are in sync. Skoe and colleagues (2011) found that the group of 90 children performed according to expectation in which the greatest phase shifts were found between the first 50 ms of /ba/ and /ga/ because of the differences in their frequencies. The cross-phaseogram has typically been used for group comparisons, but never as an individual difference measure. The current study is the first to use it to compare differences between individual participants.

Current Study

While subcortical structures were hypothesized to play an important role in auditory language processing, it is important to reiterate that Tecoulesco et al. (in press) did not suggest that syntax is entirely processed in the brainstem. Rather, the brainstem seems to be a necessary gateway to the cortex where language is further and more deeply interpreted. A smooth, speedy, and stable gateway will allow for highly active signals to be sent to the cortex, whereas slower, less stable, and less reliable gateways results in fragmented, less efficient signals. This is why it is an important contribution to this field of study to understand this early component of the auditory language processing system with a focus on sentence comprehension, an aspect that has yet to be examined in detail.

The current study investigates how individual differences in ABR and individual differences in timed-sentence comprehension might be related. The measures involved include sentence comprehension accuracy and reaction times, ABR stability, and ABR specificity. Based on the existing literature, I hypothesized that individuals with greater stability and greater specificity will have greater accuracy and faster reaction times on the timed-sentence comprehension task.

Methods

Participants

This study included 26 participants, 21 females and 5 males. Participants were college undergraduate and graduate students at the University of Connecticut and other schools. Participants' ages ranged from 19 to 27 years with a mean age of 21.3 years (SD = 2.3 years). Participants were recruited based on the following criteria: (1) monolingual English speaking from birth (raised in a monolingual household) and (2) have normal hearing (no history of hearing loss). These criteria created generalizability to achieve relative uniformity across the sample; doing so allowed for correlations between language task findings and ABR components without the influence of confounding factors such as processing of/exposure to a second language or hearing loss. The recruitment process included announcements in the UConn Daily Digest, emails to participants in previous ABR studies, word-of-mouth, and providing lab hours for research assistants in the Child Language Lab and Auditory Brainstem Response Lab. Those who were not provided lab hours for their participation were compensated $20 for the two-hour session.

Each participant finished the Nelson-Denny Reading Test, a vocabulary definition test with 80 multiple choice questions that varied in difficulty with five answer choices each (Nelson & Denny, 1929). Participants' scores ranged from 50 to 77 out of a possible score of 80, with the mean score being 67.2 (SD = 7.3); the minimum, maximum, and mean values of this sample were higher than the normative mean test scores for both college freshmen (49.40, SD = 15.18) and college seniors (62.72, SD = 11.55) (Haught & Walls, 2002).

Materials

Sentence Comprehension Stimuli. The timed-sentence comprehension task consisted of twenty 20-word sentences that varied in complexity and structure. They included five passive sentences (hypothesized to be the least difficult), five active-conjoined sentences, five sentences containing a subject-relative center-embedded clause, and five sentences containing object-relative center-embedded clauses (hypothesized to be the most difficult). Four practice sentences—one of each structural type—were also created:

Passive: *The cat with orange fur was being chased by the grey dog with black ears.*

Active-conjoined: *The duck is running away from the brown cow and is running with the pig.*

Subject-relative: *The boy who was wearing a red shirt was chasing the brown dog.*

Object-relative: *The cow that was being chased by the horse was running away from the boy.*

The sentences were recorded using the researcher's voice and edited on the Praat program to create auditory stimuli. These stimuli were pseudo-randomized based on the following criteria in order to create four different test versions: none of the same sentence-type could occur consecutively, and no more than two sentences with the same number of distinctions could occur consecutively. Number of distinctions refers to the number of cues within the sentence or a correct match to be distinguished (i.e. what is different between the pictures that cues the correct answer); the correct answer is typically more difficult to identify if there are fewer distinctive cues. The Appendix contains each sentence, its type, the number of distinctive cues, and the corresponding picture pair.

The visual stimuli for the timed-sentence comprehension task were originally created for the Kempler Sentence Comprehension Test and the Formulaic and Novel Language Comprehension Test, both image sets available on Kempler's Emerson College website (Kempler & Van Lancker Sidis, 1996, http://word.emerson.edu/daniel_kempler/kempler-sentence-comprehension-testt/). The original line drawings were edited on the Paint S photo-editing application to add color. The visual stimuli were paired with the corresponding auditory stimuli in the program PsychoPy so that the appropriate sentences were heard before the presentation of the two picture options, one of which was the correct match (see Figure 6).

Nelson Denny Stimuli. The Nelson-Denny Reading Test (Brown et al., 1993) is a vocabulary test consisting of 80 multiple choice questions with five possible answer choices each. The questions, which vary in difficulty and form, test the participant's knowledge of word definitions; for example: *A rigorous teacher is: (a) righteous, (b) hard to believe, (c) satisfying, (d) strict, (e) direct* (answer: d), or *Dependable means: (a) friendly, (b) changeable, (c) serious, (d) reliable, (e) dull* (answer: d) (North Carolina Wildlife Resources Commission). The Nelson-Denny Reading Test Instructor's Manual provides normative scores for high school students (first and fourth years), college students (first and fourth years), and professional students (medical, dental, PT). The normative scores relevant for the current study are those of college freshmen, with a mean score of 49.40 (SD = 15.18), and college seniors, with a mean score of 62.72 (SD = 11.55) (Haught & Walls, 2002).

ABR Stimuli. ABR task stimuli descriptions and procedure drew heavily from Tecoulesco et al., (in press). A 100-microsecond click stimulus was presented twice, 3,000 times per each trial. For the speech recordings, a 40-millisecond /da/ speech stimulus was played twice, 5,000 times per each trial. A 170-millisecond /ba/ speech stimulus was played 4,200 times for one trial, and a 170-millisecond /ga/ speech stimulus 4,200 times for one trial. The average of all trials for each stimulus was calculated on BrainVision. The pre-recorded stimuli were provided by Dr. Erika Skoe (2015 & 2017) and presented to participants through ear inserts in the sound booth.

Experimental Setup

The study was conducted in Dr. Erika Skoe's (SLHS) Auditory Brainstem Response Lab at the UConn Storrs campus. The ABR lab contains a sound booth where the recording takes place, an audiometer, otoscope, and DPOAE recorder for hearing screenings, a projector and computer for video to play in the booth during the recording, and two computers: one for the BrainVision program to collect and process the data recorded, and one on which MATLAB produces and sends the sounds into the participants' ear inserts. Materials used specifically for the ABR portion of the study include a set of three electrodes, ear inserts, NuPrep Gel for removing oil and dry skin, Ten20 Paste for electrode-to-skin connection, tape for additional adhesion, and alcohol swabs for cleaning. The sentence comprehension task and Nelson Denny Reading Test were presented on a separate laptop.

Computer Programs. In addition to the BrainVision and MATLAB programs previously mentioned, other computer applications used for development of the sentence comprehension task include the Praat computer sound editing system to record the sentences heard by the participants during the experiment (Boersma & Weenink, 2018), Paint S for Mac to edit and color the originally black-and-white stimuli, and the PsychoPy software (Peirce et al., 2019)—used to create experimental tasks for neuroscience and psychology research—to put the audio and visual stimuli together to build the actual timed-sentence comprehension task; Statistical Package for the Social Sciences (SPSS) is the software that was used for data analysis (IBM Corp). MATLAB was also used to quantify values for ABR measures of stability and specificity.

Procedure

Hearing Screening. Following the explanation of the experimental procedures and signing of consent, participants went through a three-part hearing screening. First, an otoscope was used to look into each of the participants' ears to make sure they were clean and there was no blockage. Next, Distortion Product Otoacoustic Emissions (DPOAEs) were recorded using an OAE screener. DPOAEs are the signals produced in response to cochlear hair cell movement caused by auditory stimulus, but distortion occurs due to the cochlea's spiral shape (Ramos et al., 2013). While the participant hears sounds from their ear insert, their outer hair cells change shape to amplify and propagate the sound; this movement of the hair cells produces sound that can be recorded and translated numerically by the screener (Ramos et al., 2013). A test in which the participant heard six different frequencies was conducted using the DPOAE screening device. The end of the ear insert contains a microphone so the sounds being produced by the moving hair cells could be recorded, translated into numerical values, and assessed ("pass/fail"). The DPOAEs were recorded for each ear one at a time.

The final portion of the hearing screening was an audiometer test conducted in the sound booth. Ear inserts were connected to the left and right hearing-screening cords and fit into each of the participants' ears. They were given a clicker and instructed to press the button any time they heard a sound in either ear, and that they could speak into the booth and would be heard through a headset out in the computer area where the audiometer is located. The audiometer was set to the following parameters: pulse, tone, insert, right or left ear, and 20 decibels. The participant heard three-pulse sounds at various frequencies (250 Hz, 500 Hz, 1000 Hz, 2000 Hz, 4000 Hz, 8000 Hz). If the participant did not hear a particular frequency at 20 decibels, the sound was increased to 25 decibels. Participants were able to continue on to with the remainder of the study if they pressed the button in response to all the frequencies at 20 decibels or no more than one frequency at 25 decibels.

Timed-Sentence Comprehension & Computer Tasks. This task, created via PsychoPy (Peirce et al., 2019), assessed participants' sentence comprehension speed and accuracy. Participants were instructed that they would hear sentences of varying difficulty when the fixation cross appeared, then they would see a screen with two pictures, and they must choose the picture that matches the sentence they heard. If the picture on the left matched, they were instructed to press the 'F' key on a standard keyboard, and if the picture on the right matched, they were instructed to press the 'J' key. Once the participant pressed either 'F' or 'J' on the keyboard, the fixation cross appeared again while the next sentence was played aloud. Before going through the twenty sentences, participants completed four practice trials—one of each sentence type, listed in the Materials section—to gain understanding of the task before they officially began. During the actual task, their reaction times and answers (incorrect coded as 0, correct coded as 1) were stored by PsychoPy. No feedback was provided to the participants for the practice trials nor the test trials.

Four versions of the timed-sentence comprehension task were created. Versions A, B, C, and D varied in the order by which the stimuli were presented, as the audio and corresponding visual stimuli were pseudorandomized. Fallon et al. (2006) used a quasi-random order for their 144 sentences presented to participants so that no more than three of the same sentence-type were presented consecutively; the current study used 20 sentences (see Appendix), so tighter constraints were applied in the timed-sentence comprehension task as follows: (1) none of the same sentence-type occurred consecutively and (2) no more than two sentences with the same number of distinctions occurred consecutively. These constraints created four different pseudo-randomized versions of the task. Participants were randomly assigned which version they completed. Following the administration of the timed-sentence comprehension task, the Nelson-Denny Reading Test was conducted on the laptop. No feedback was provided to the participants on their performance during the test or upon completion.

Auditory Brainstem Response. To record ABR, a connection was made using three electrodes: one on the front of the forehead (grounding electrode), the top of the head (CZ; active electrode), and on the right ear (reference electrode). The connection was made by first using NuPrep Gel on a Q-tip to scrub the skin where the electrode would be placed; removing any dry skin or excess oils allowed for a better connection to be made. Ten20 Paste was used to adhere the electrodes to the skin, with small pieces of tape as an additional adhesive layer on the forehead and right ear. Once the electrodes were placed, the participant was brought into the sound booth and sat in a reclining chair. The electrodes were connected to the power box and the impedance (i.e. interference) levels for each electrode were checked on BrainVision. The goal was to keep impedance low so that the greatest connection can be made between the electrodes and the skin; the ideal value of impedance was 0 kiloohms, although 1 kiloohm was also acceptable. If the impedance was higher, the electrodes were adjusted to lower the value and thus improve the connection being made with the skin. Participants were instructed to lean back and relax, remaining as still as possible during the procedure so as to get a greater number of accurate trials. They were also told to relax their eyes and their jaw, as the tension could also interfere with the ABR recording. The click, /da/, /ba/, and /ga/ stimuli were presented through the ear inserts, during which they watched a silent film of their choice (with captions) projected onto the wall in the sound booth. After the recordings were finished, the participants' electrodes were disconnected, ear inserts removed, and cleaned up with alcohol wipes to remove the Paste and Gel.

The order of presentation for this study was as follows: hearing screening, timed-sentence comprehension task, Nelson-Denny Reading Task, ABR. The tasks were presented in this order because the conditions of the sound booth where the ABR is recorded (dark, reclined in a comfortable chair) could potentially cause participants to become tired and affect any subsequent behavioral performances. A phonetic discrimination task (Tecoulesco et al., in press) was also performed on the laptop, but was not be analyzed for this study.

Data Analysis

Timed-Sentence Comprehension Measures. PsychoPy stored the correct/incorrect responses and the reaction time for each question for each participant. Average accuracy and average reaction times for the four sentence types, as well as the overall accuracy (out of 20 questions) and overall average reaction time, were calculated. Comparisons for each measure were made between the four different sentence types to confirm grammatical variation between them and to assess the effects of sentence type on accuracy and reaction time using repeated measures ANOVAs and paired sample t-tests on the SPSS program. Correlations between the measures of accuracy and reaction time as well as Nelson-Denny scores were run using the same program.

ABR Stability. The stability measure of the ABR data recorded in response to the /da/ speech stimulus was originally calculated based on 5000 repetitions. However, not all participants had 5000 repetitions recorded; this may have been caused by movement or muscle tension, causing BrainVision to throw out those trials. Therefore, the analysis was re-run on MATLAB using 3700 repetitions in order to include the greatest number of participants possible. For actual analysis, MATLAB divided each participants' 3700 repetitions into two waves, then cross-correlated them with each other; two measures of such stability were assessed—one for the complete 40 millisecond /da/ duration and one for just the formant transition period of 10-20 milliseconds—to produce a correlation coefficient for each, R.

ABR Specificity. /Ba/ and /ga/ speech stimuli were analyzed using the cross-phaseogram developed by Skoe, Nicol, and Kraus (2011); in this particular study we implemented a novel analysis to assess individual differences. When observing the cross-phaseogram, /ba/ and /ga/ were compared, yielding colors representing differences between the stimuli. The normative pattern that was expected was red during the earlier portion of the time—from where ga leads ba (as it has a lower frequency)—indicative of greater distinction between two different sounds. The later portion of time would be expected to appear green in color because the /ga/ and /ba/ stimuli are equivalent in ending in /ah/; thus, these /ah/s would not be discriminated by the auditory system. The cross-phaseograms were then translated to numerical values drawing upon the analysis by Neef, Schaadt, and Friederici (2017), as follows: In order to see how different the /ba/ and /ga/ sounds were to the participant, ranges of time and ranges of frequencies were selected to form a block within the plot; the points—representing interpretive differences between frequencies by the auditory brainstem—within that block were then averaged using MATLAB, since it is not as accurate to interpret just a singular point. Numerical values representing how different the participant is processing /ba/ and /ga/ were analyzed at the frequency ranges 400-720 Hz ("mid") and 720-1000 Hz ("high"), each from 20-40 milliseconds (when the sounds differ) and from 50-150 milliseconds (when the sounds are the same) (Neef et al., 2017).

Results

Timed-Sentence Comprehension Task

Accuracy. The mean for the total number of questions correct for all 26 participants was 16.269 (SD = 1.809), resulting in the average percentage correct [out of 20] of 81.35% (see Table 3). T-tests revealed that more passives were responded to accurately than subject-relatives ($t(25) = 0.848$, $p = 0.030$); passives also elicited more correct responses than object-relatives ($t(25) = 3.268$, $p = 0.003$). Additionally, more active conjoined sentences were responded to correctly compared with object-relatives ($t(25) = 2.813$, $p = 0.009$). (See Figure 7 and Table 5).

Reaction Time. The mean reaction time for all participants was 3.165 seconds (SD = 0.979), with a maximum overall average reaction time of 5.3349 seconds and a minimum of 2.0927 seconds (see Table 4). T-tests revealed that passives were responded to more quickly than subject-relatives ($t(25) = -4.941$, $p < 0.001$), and object-relatives ($t(25) = -6.617$, $p < 0.001$); additionally, active conjoined sentences were responded to more quickly than subject-relatives ($t(25) = -3.566$, $p = 0.001$) and object-relatives ($t(25) = -6.129$, $p < 0.001$), and subject-relatives were responded to more quickly than object-relatives ($t(25) = -3.681$, $p = 0.001$). (See Figure 8 and Table 6).

Relationships with ABR measures

Stability. Participants with higher accuracy in responding to passive sentences also demonstrated greater stability in their ABRs to the /da/ stimulus ($R = 0.609$, $p = 0.002$). While not significant, trending relationships were found with reaction time for both passive sentences and object-relative sentences (see Table 7). There were no significant correlations between stability and reaction time, nor were there any correlations with Nelson Denny scores (see Table 8).

Specificity. Each of the four cross-phaseogram groups (mid-frequency, high-frequency, early timing, later timing) were analyzed for relationships with accuracy measures (total and for each sentence type) and reaction time measures (overall average and for each sentence type). No significant correlations were found with the accuracy measures (see Table 9).

However, as shown in Table 10, a number of significant correlations emerged between specificity and the reaction time measures. For the mid-frequency range, participants with shorter overall RTs, shorter RTs for passive sentences, and shorter RTs for subject-relative sentences, also had better specificity; trends for this range were found among reaction time for active conjoined sentences and for object-relative sentences.

Correlations were also found between a number of reaction time measures and the frequency range from 720 to 1000 Hz, also during the time frame of 20 to 40 milliseconds. For this high-frequency range during this early time interval, participants with shorter average RTs, shorter RT for passive sentences, shorter RTs for active conjoined sentences, and shorter RTs for subject-relative sentences had better specificity. No correlations were found at either frequency range from 50 to 150 milliseconds. These findings are summarized in Table 10.

No significant correlations emerged with the participants' Nelson Denny scores.

Discussion

The current study investigated the relationships between ABR with timed-sentence comprehension. Sentence comprehension measures of accuracy and reaction time (RT) were compared for the four different sentence types tested in the language task. Regarding accuracy, as sentence type difficulty increased, participant accuracy decreased; significant differences were found between accuracy for passives and subject-relatives, passives and object-relatives, and active conjoined sentences and object-relatives. Regarding RT, the means for each sentence type were slower (i.e. increased) as sentence type difficulty increased. RTs for passive sentences were found to be significantly faster than those of subject-relatives and object relatives. RTs for active conjoined sentences were significantly faster than those of subject-relatives and object-relatives. RTs also significantly differed between subject-relative and object-relative sentences. These sentence-comprehension measures were then analyzed for relationships with ABR stability and specificity. The only significant correlation with stability was for passive sentence accuracy: Individuals with greater ABR stability had higher scores for passives. ABR specificity and reaction times yielded the most significant correlations, all of which were found when analyzing the first 20-40 millisecond portions of the /ba/ and /ga/ stimuli. For the mid-frequency range, participants with shorter RTs overall, for passives, and for subject-relatives, had better specificity. For the high-frequency range, participants with shorter RTs overall, for passives, for active conjoined sentences, and for subject-relatives, had better specificity.

Sentence Comprehension

The sentence comprehension findings were as predicted for accuracy and RT: on average, participants were less accurate and had slower RTs for the sentence types that were more complex, syntactically. This was expected because more complex sentences are structurally more difficult, requiring the listener to listen to details more carefully, which takes more time. For example, in object-relative sentences (e.g. *The cow that was being chased by the horse was running away from the boy*.), participants had to determine what the object of the action described. The same pattern was seen among mean RTs, which were fastest among the easiest sentence type and slowest among the most difficult type. This was expected because listeners are more likely to make mistakes when interpreting more complex sentences, requiring greater time to decode the information correctly.

ABR Stability

Individuals with greater stability were predicted to have greater accuracy and faster RTs on the timed-sentence comprehension task. This was expected because the findings from the previous study by Tecoulesco, et al., (in press; Tecoulesco, 2018) found that greater /da/ stability correlated with grammatical performance. This relationship was found by assessing performance on the Formulated Sentence test of the Clinical Evaluation of Language Fundamentals, Fifth Edition (CELF-5); this test assessed participants' ability to form grammatically correct spoken sentences of increasing length and complexity, and served as a measure of syntactic capability. Higher Formulated Sentences scores—indicative of better grammatical performance—were associated with greater /da/ stability. (Tecoulesco, et al., in press).

This hypothesis was not supported by the current data; that is, the Tecoulesco et al., (in press) finding was not replicated. Besides a correlation between stability and passive sentence accuracy, there were no other significant findings. Stability was likely found to be associated with grammatical production rather than with syntactic/semantic comprehension skills required by the timed-sentence comprehension task. This may be explained by the difference of production being tested by Tecoulesco et al., (in press) and comprehension being tested in the current study. Greater stability results in more accurate phonological representations, as stable brainstems consistently process the same sound the same way. This accuracy may allow for the development of better grammar skills; individuals can thus replicate (i.e produce) the proper grammar they have encoded (through conversation and being surrounded by verbal language).

Since stability is associated with grammatical production rather than understanding semantics, sentence comprehension may thus be explained by a different measure: specificity.

ABR Specificity

Individuals with greater specificity were predicted to have greater accuracy and faster RTs on the timed-sentence comprehension. While no significant correlations were found between specificity and accuracy, significant relationships were found with respect to RT: participants who had better specificity had shorter (i.e. faster) RTs for average reaction times, passive sentences, active conjoined sentences, and subject-relative sentences. Thus, the hypothesis regarding RT was supported. The findings extend the Skoe, Nicol & Kraus (2011) study, as the current study is the first to use the cross-phaseogram—originally designed and typically used for group comparisons— to compare variation between individuals.

Significant relationships between specificity and sentence comprehension may be explained by the anatomical relationship with the inferior colliculus. This subcortical structure integrates auditory signals and recognizes frequencies, which is particularly important for discriminating between stimuli that differ in frequency (such as /ba/ and /ga/). From this, it can be inferred that specificity is localized in the inferior colliculus, and so participants who were good at resolving differences between segments early on (when the sounds differ) and at high frequencies have well-functioning inferior colliculi.

The current study revolved around comprehension rather than production, which may be why relationships were found between reaction time and specificity rather than stability. During the task, participants had to interpret important segmental differences of the complex stimuli, such as the subject of the sentence, the action performed, and the object of the verb (what/who was being acted upon). For example, the sentence with the slowest mean reaction time of all the stimuli was the following object-relative sentence: *the little boy who the girl with the ponytail chased was running away from the dog with the black ears*. In order to make a decision between the two pictures, participants had to understand who was being chased/running away and by/from whom. In order to interpret this complex information quickly, participants had to have greater capacity to process sounds. Being able to differentiate sounds better allowed participants to process the information they heard more quickly, thereby choosing their answer faster. This demonstrates that in order to understand complex sentences well and quickly, individuals must have a brainstem that captures and distinguishes different sounds accurately.

Limitations & Future Directions

There were some limitations of this study that could be improved when moving forward with similar research. Using a small sample size meant that there were fewer individuals to observe variability among; moreover, there were many more female participants compared to male participants. Additionally, all participants were college undergraduate and graduate students, so they were all at similar academic and language levels. A larger sample size with a more equal gender ratio and educational diversity would allow us to better generalize the findings.

Regarding the timed-sentence comprehension task, working memory could also be an influence on participants' performance since they had to choose the correct picture after hearing the sentence first. Since a working memory task was not included, this could potentially be a confounding variable as participants had to use working memory to retain the information verbally presented by the previously heard sentence when choosing between the two pictures (Fallon et al., 2006). Lastly, technological issues early in the ABR set-up process required some participants to be recorded multiple times and may have impacted the accuracy of the collected data.

Future directions for this research include replicating this same study with children, and incorporating a working memory task into future set-ups to test its influence on auditory sentence comprehension. Future studies should also compare differences in educational level, as this may influence variation in language and phonological encoding abilities. Kidd et al. (2018) used education level as a measure of socioeconomic status among adults, which was associated with individual differences in language attainment; they found that individuals who found themselves in language-rich settings also had greater language proficiency (Kidd et al., 2018). Thus, education level could potentially influence language ability, and further research can incorporate ABR to assess if such demographic differences may impact subcortical function that has been shown to correlate with language.

In addition to continuing the study of ABR's influence on processing complex stimuli, researchers may also use ABR to assess individuals with language deficits, offering possible further explanation of subcortical contribution to various aspects of language.

The relationship between ABR and timed-sentence comprehension in adults is an aspect of the field that must be investigated further in order to fully understand subcortical contributions to language. So far, brainstem assessments show us that auditory processing skills that are used when interpreting verbal language impact how long it takes to interpret that information in order to respond appropriately. They also connect certain aspects of auditory processing with particular aspects of language. While cortical assessments are important, they do not incorporate part of the auditory system that is fundamental to our everyday language comprehension. Neural language encoding involves the ability process of sounds and the complex functions of the brainstem, without which verbal language cannot be understood. Subcortical assessments provide us with knowledge of the early steps in language encoding that influence our overall comprehension abilities.

Tables and Figures

Table 1. Sentence types used in Fallon et al. (2006)

Sentence Type	Definition	Example
Active-Conjoined	Two clauses are joined together and the subject performs the actions of the verb in each clause	The man *is walking the dog* and *wearing a hat.*
Subject-Relative	Clause embedded in center of sentence tells us about the subject that carries out the action described in the clause	The man [*that is walking the dog*] is wearing a hat.
Object-Relative	Clause embedded in center of sentence tells us about the object of the action described	The dog [*that the man is pulling*] chases a squirrel.

Definitions and examples of sentence types used in sentence comprehension study: active-conjoined, subject-relative, and object-relative.

Table 2. Wh-movement study sentences

Short Control	"The townspeople hoped that the cameraman knew *whether* the mayor would honor the soldiers before the fireworks."
Short Movement	"The townspeople hoped that the cameraman knew *which soldiers* the mayor would honor (__) before the fireworks."
Long Control	"The cameraman knew *whether* the townspeople hoped the mayor would honor the soldiers before the fireworks."
Long Movement	"The cameraman knew *which soldiers* the townspeople hoped the mayor would honor (__) before the fireworks."

Examples of short control, short movement, long control, and long movement sentences; wh-words in control sentences in green, moved wh-word and original position in red (Rogalsky et al., 2015).

Table 3. Timed-sentence comprehension task accuracy results

	Passive Sentences	**Active Conjoined Sentences**	**Subject Relatives Sentences**	**Object Relative Sentences**	**Total**
Mean	4.462	4.308	3.962	3.358	16.269
SD	0.826	0.489	1.076	1.192	1.809
Minimum	3/5	4/5	2/5	1/5	13/20
Maximum	5/5	5/5	5/5	5/5	19/20
% Correct	89.24%	86.16%	79.24%	67.16%	81.35%

Data includes mean, standard deviation, minimum correct score, maximum correct score, and percentage correct for each of the four sentence types and total score out of 20.

Table 4. Timed-sentence comprehension task reaction time results (in seconds)

	Passive Sentences	**Active Conjoined Sentences**	**Subject Relative Sentences**	**Object Relative Sentences**	**Average Reaction Time**
Mean (s)	2.675	2.839	3.278	3.869	3.165
SD	0.870	1.157	0.965	1.298	0.979
Minimum	1.7551	1.4588	1.3790	1.7493	2.0927
Maximum	5.2563	5.6101	5.3900	7.2852	5.3349

Data includes mean, standard deviation, minimum times, and maximum times for each sentence type and for average reaction times for all 20 sentences.

Table 5. Differences between sentence types for accuracy

Sentences	**t**	**df**	**p value**
Passive vs. Active Conjoined	0.848	25	0.404
Passive vs. Subject Relative	2.308	25	**0.030***
Passive vs. Object Relative	3.268	25	**0.003***
Active Conjoined vs. Subject Relative	1.563	25	0.131
Active Conjoined vs. Object Relative	2.813	25	**0.009***
Subject Relative vs. Object Relative	1.251	25	0.223

Paired sample t-test results, with statistically significant relationships marked with an asterisk.*

Table 6. Differences between sentence types for reaction time

Sentences	t	df	p value
Passive vs. Active Conjoined	-1.207	25	0.239
Passive vs. Subject Relative	-4.941	25	**0.000***
Passive vs. Object Relative	-6.617	25	**0.000***
Active Conjoined vs. Subject Relative	-3.566	25	**0.001***
Active Conjoined vs. Object Relative	-6.129	25	**0.000***
Subject Relative vs. Object Relative	-3.681	25	**0.001***

*Paired sample t-test results, with statistically significant relationships marked with an asterisk**

Table 7. Correlations between stability and accuracy

		/da/ formant transition
Total	R value	0.093
	p value (significance)	0.665
Passive Sentences	R value	**.609***
	p value (significance)	**0.002**
Active Conjoined Sentences	R value	-0.063
	p value (significance)	0.769
Subject Relative Sentences	R value	-0.055
	p value (significance)	0.798
Object Relative Sentences	R value	-0.164
	p value (significance)	0.445

Correlations between total accuracy and accuracy for each sentence type with stability, measured as the formant transition of the /da/ stimulus. Statistically significant correlations are marked with an asterisk.*

Table 8. Stability correlations with Nelson Denny score and reaction times

		/da/ formant transition
Nelson Denny Score	R value	-0.231
	p value (significance)	0.278
Average Reaction Time	R value	0.342
	p value (significance)	0.102
Passive Sentences	R value	*0.347*
	p value (significance)	*0.096*
Active Conjoined Sentences	R value	0.259
	p value (significance)	0.222
Subject Relative Sentences	R value	0.247
	p value (significance)	0.244
Object Relative Sentences	R value	*0.386*
	p value (significance)	*0.062*

Correlations between Nelson Denny scores, average reaction time for all 20 sentences, and reaction time for each sentence type with stability, measured as the formant transition of the /da/ stimulus. No statistically significant relationships were found. Trends are in italics.

Table 9. Correlations between specificity and accuracy

		Mid: 20-40 s	**Mid: 50-150 s**	**High: 20-40 s**	**High: 50-150 s**
Total	R value	-0.214	0.026	-0.096	-0.169
	p value (significance)	0.315	0.902	0.657	0.430
Passive Sentences	R value	-0.115	0.058	-0.111	-0.096
	p value (significance)	0.592	0.788	0.607	0.654
Active Conjoined Sentences	R value	0.022	-0.146	0.168	0.064
	p value (significance)	0.920	0.495	0.433	0.766
Subject Relative Sentences	R value	0.053	0.331	0.198	-0.025
	p value (significance)	0.806	0.114	0.354	0.906
Object Relative Sentences	R value	-0.297	-0.207	-0.293	-0.194
	p value (significance)	0.159	0.333	0.165	0.363

Correlations between total correct and accuracy for each sentence type with ABR specificity at mid-frequency range during early/later timing and high-frequency range during early/later timing. No statistically significant relationships were found.

Table 10. Specificity correlations with Nelson Denny score and reaction time

		Mid: 20-40 s	**Mid: 50-150 s**	**High: 20-40 s**	**High: 50-150 s**
Nelson Denny	R value	-0.367	-0.076	-0.133	0.009
	p value (significance)	0.077	0.725	0.536	0.966
Average Reaction Time	R value	**-.454***	-0.089	**-.483***	0.023
	p value (significance)	**0.026**	0.678	**0.017**	0.917
Passive Sentences	R value	**-.466***	-0.130	**-.459***	0.185
	p value (significance)	**0.022**	0.545	**0.024**	0.387
Active Conjoined Sentences	R value	*-0.393*	-0.084	**-.461***	-0.173
	p value (significance)	*0.057*	0.698	**0.023**	0.419
Subject Relative Sentences	R value	**-.466***	-0.079	**-.556***	-0.001
	p value (significance)	**0.022**	0.714	**0.005**	0.996
Object Relative Sentences	R value	*-0.367*	-0.050	-0.334	0.097
	p value (significance)	*0.078*	0.815	0.110	0.654

Correlations between Nelson Denny scores, average reaction time for all 20 sentences, and reaction time for each sentence type with ABR specificity at mid-frequency range during early/later timing and high-frequency range during early/later timing, statistically significant correlations marked with an asterisk. Trends are in italics.*

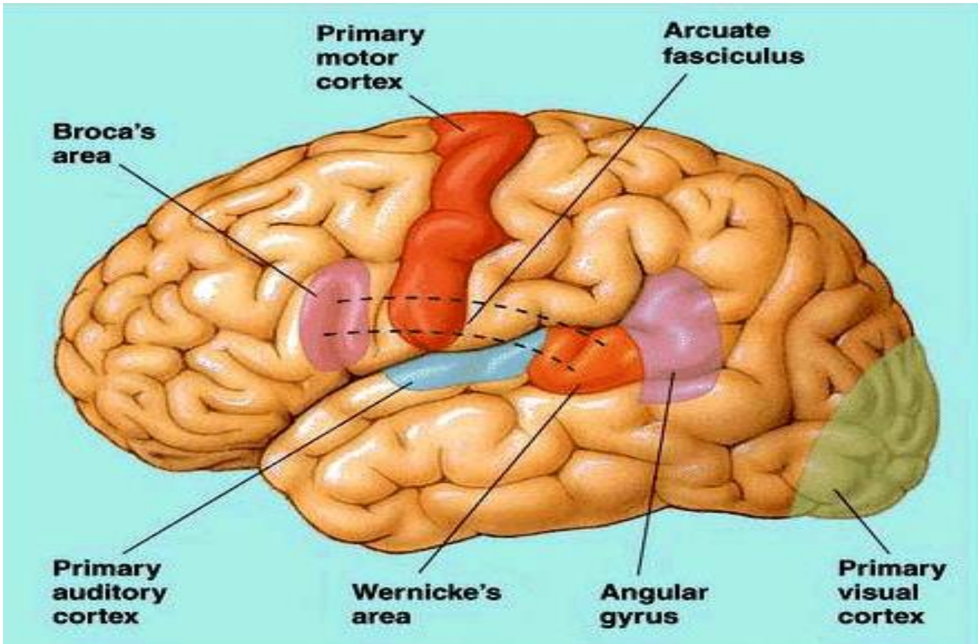


Figure 1. The Perisylvian area and other language structures of the cerebral cortex (Pinel, 2000).

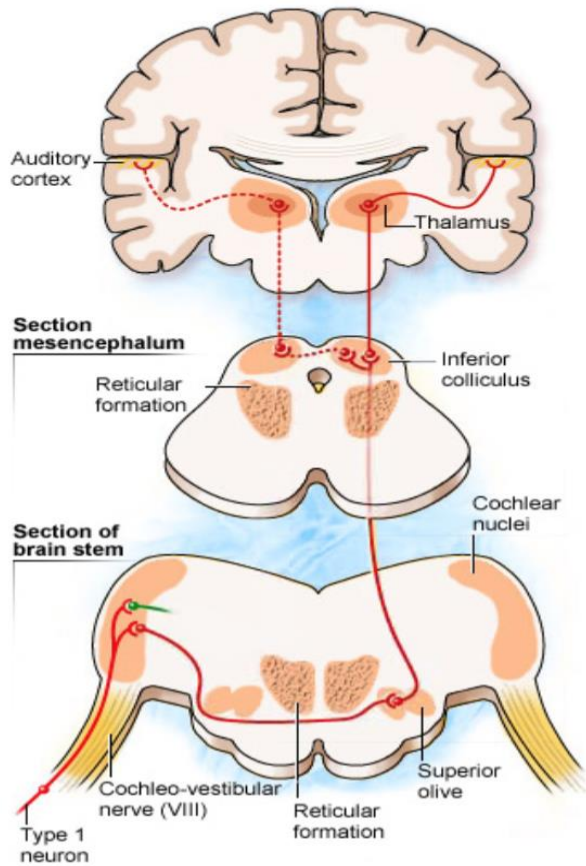


Figure 2. Sound enters the cochlea in the ear and a signal is transmitted via the auditory nerve to the brainstem, continuing up to the language areas of the cortex (Pujol & Irving, 2016).

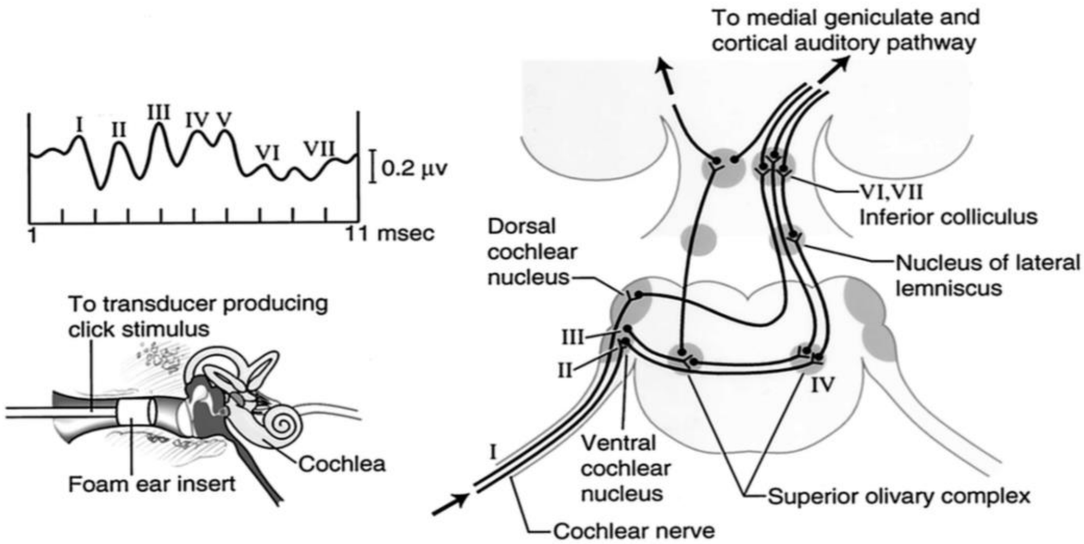


Figure 3. ABR Waves I-V and corresponding sites of production along the brainstem (Banoub et al., 2003).

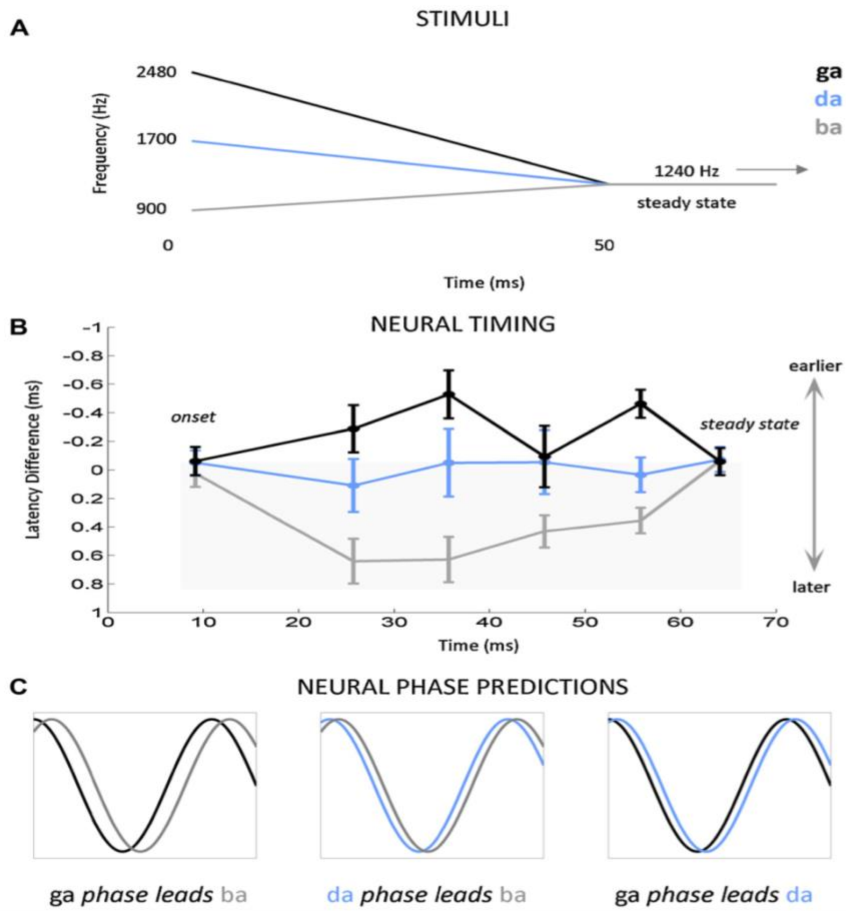


Figure 4. Differences between /ba/ and /ga/ wave phases based on frequency and latency (Skoe et al., 2011).

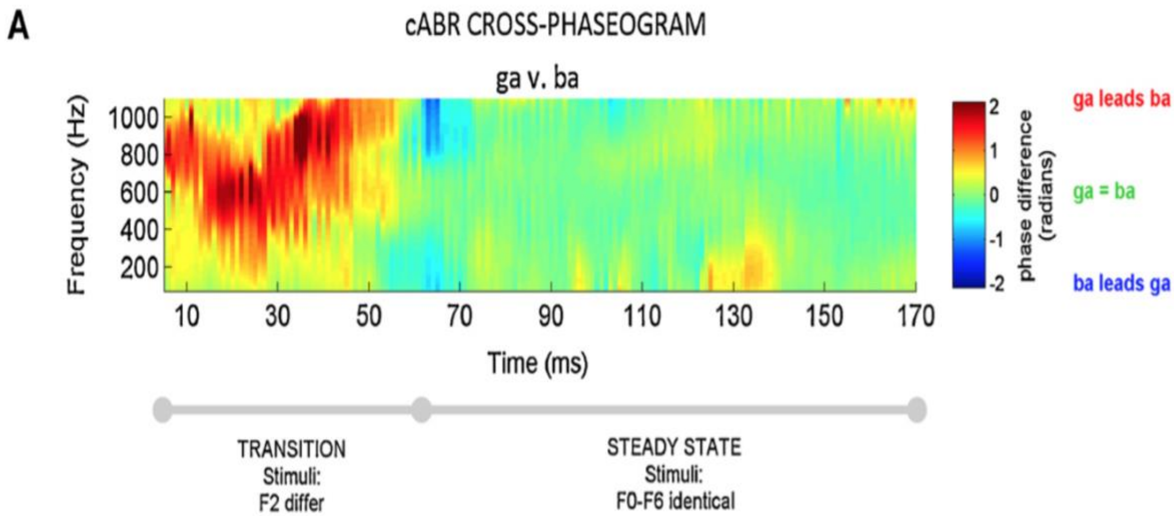


Figure 5. Cross-phaseogram depicting discrimination between /ba/ and /ga/ stimuli (Skoe et al., 2011).

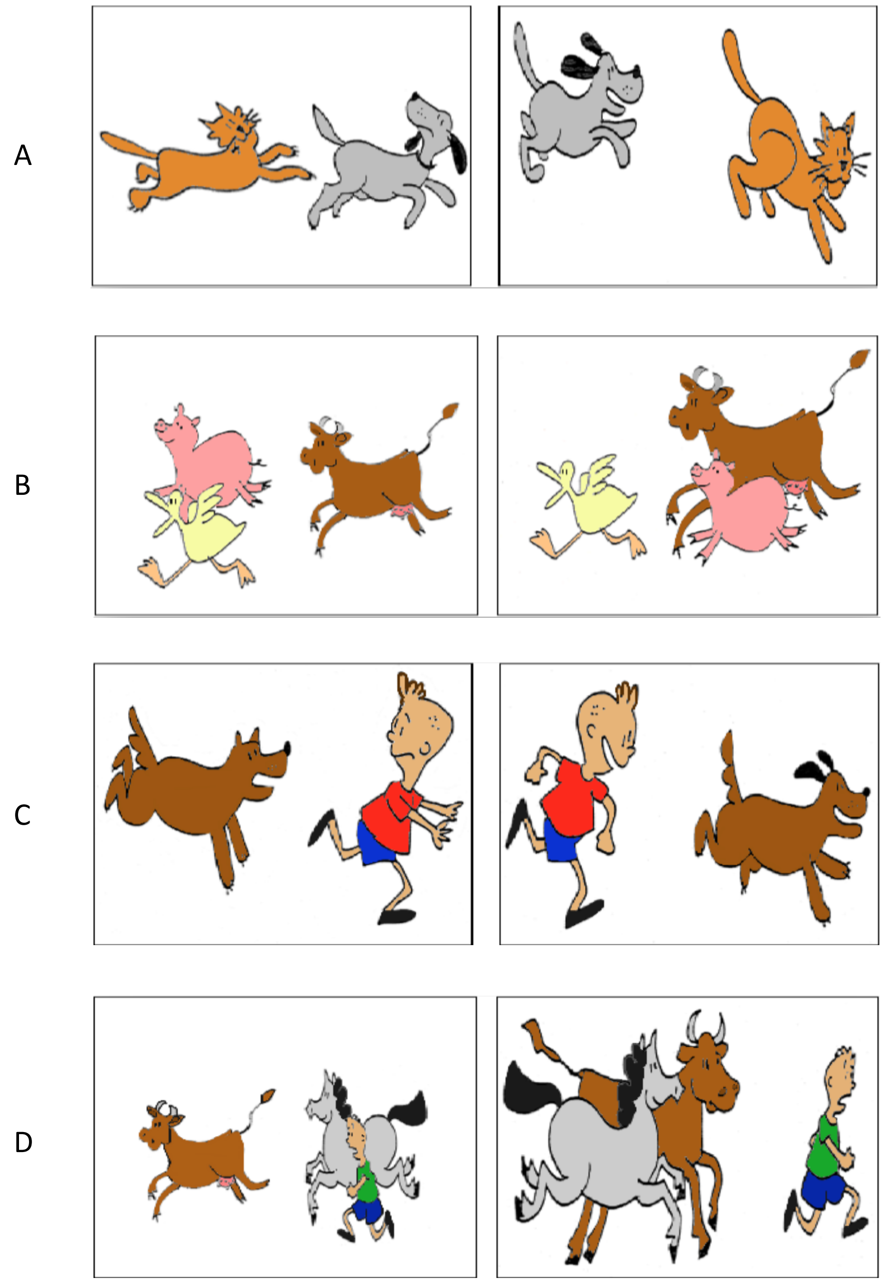


Figure 6. Picture pair stimuli and corresponding sentence of each type: **(A)** Passive: *the cat with orange fur was being chased by the grey dog with black ears* (match: right); **(B)** Active-conjoined: *the duck is running away from the brown cow and is running with the pig* (match: left); **(C)** Subject-relative: *the boy who was wearing a red shirt was chasing the brown dog* (match: right); **(D)** Object-relative: *the cow that was being chased by the horse was running away from the boy* (match: left).

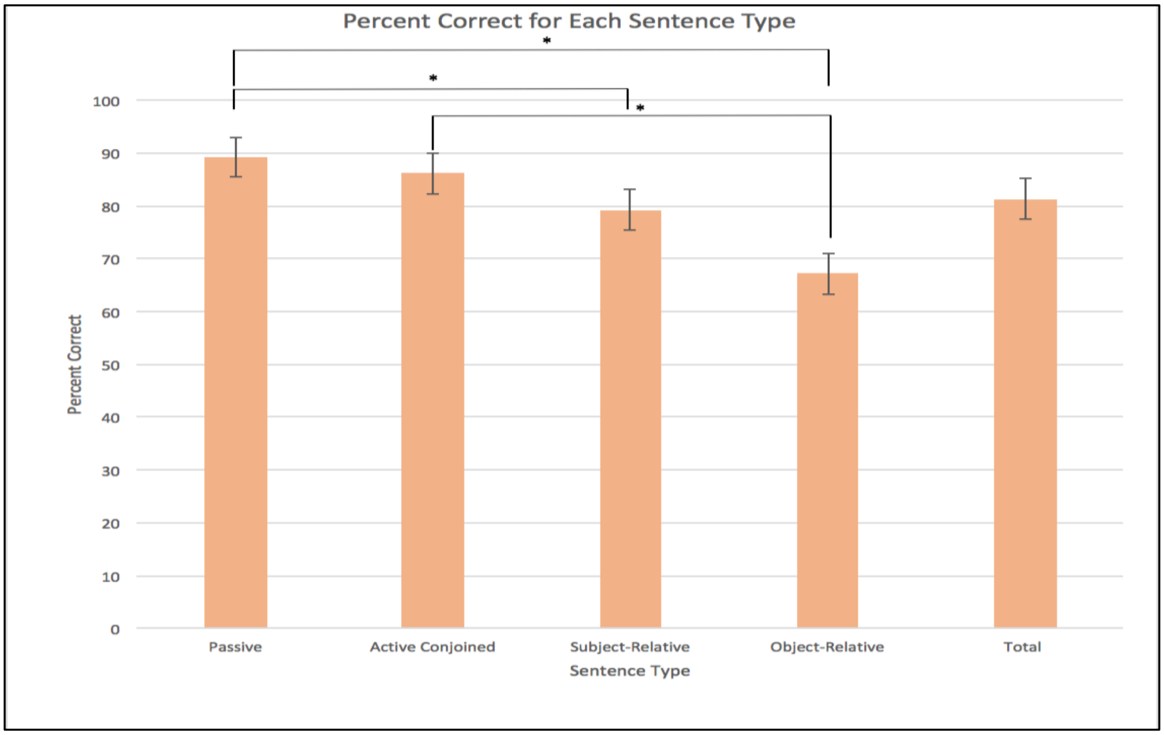


Figure 7. Percent correct for each sentence type and total score, with significant differences marked with an asterisk*.

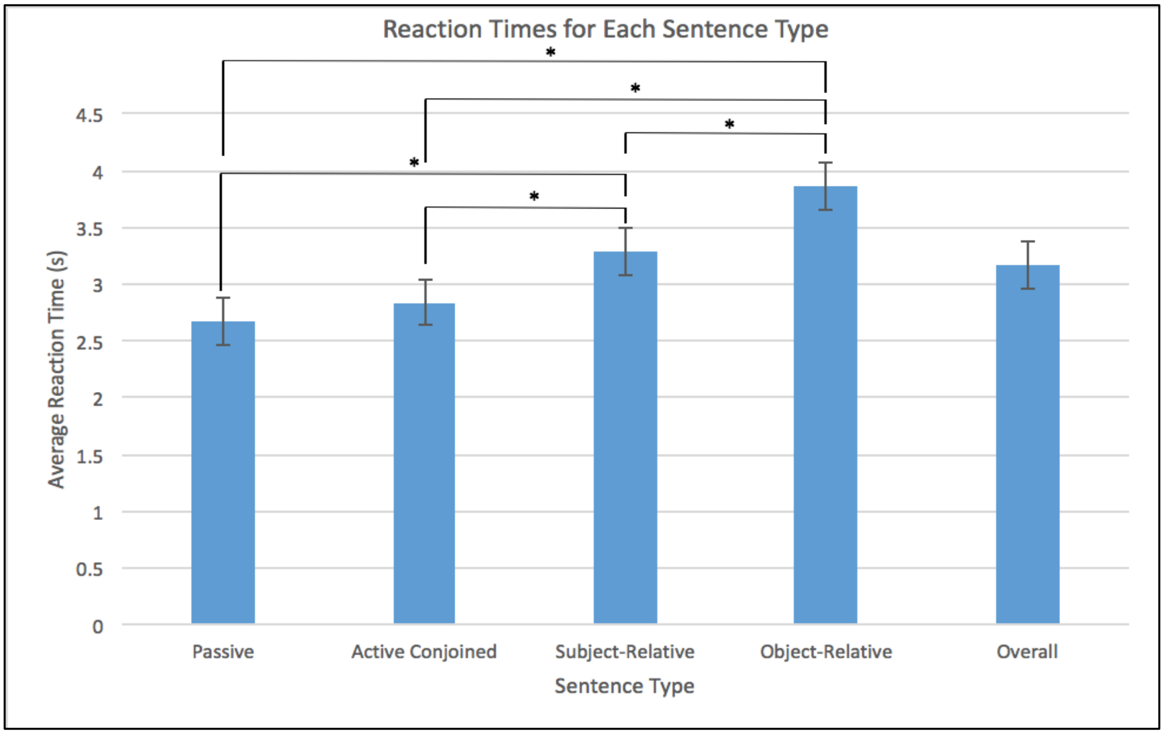
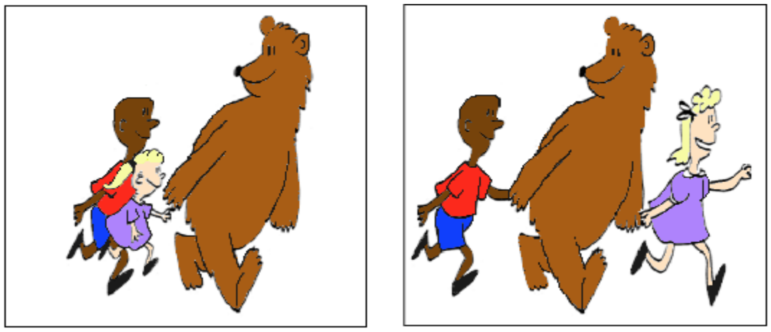


Figure 8. Average reaction times for each sentence type and overall reaction time for all 20 sentences, with significant differences marked with an asterisk*.

Appendix

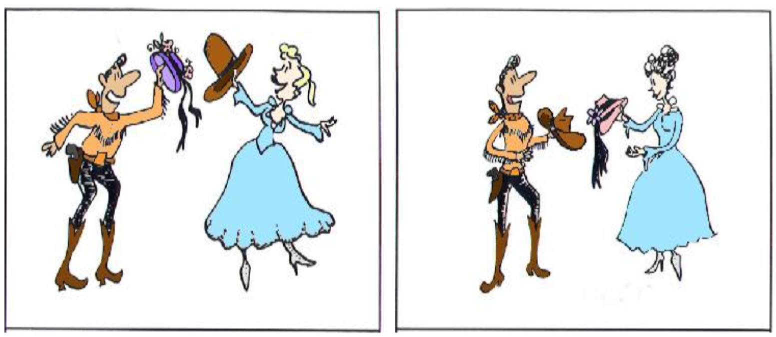
Passive Sentences

1. The bear looking back at the boy in the red shirt was being pulled by the girl with blonde hair.



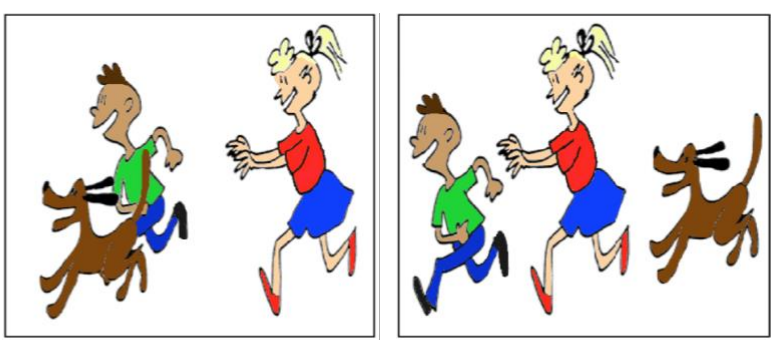
Number of Distinctions: 1
Answer: Right

2. The woman in the blue dress was given a pink hat with black ribbon by the man in a costume.



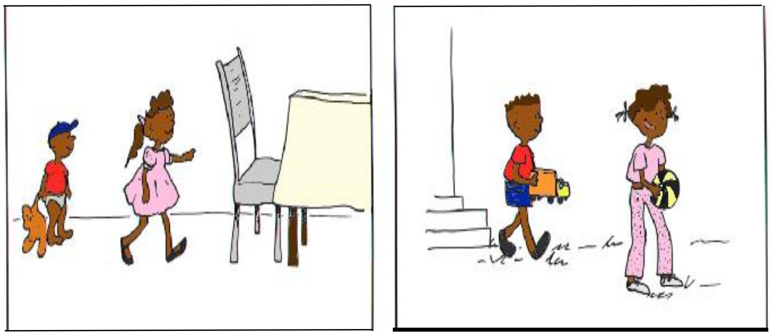
Number of Distinctions: 1
Answer: Right

3. The brown dog and the boy with brown hair were being chased by the blonde girl wearing a red shirt.



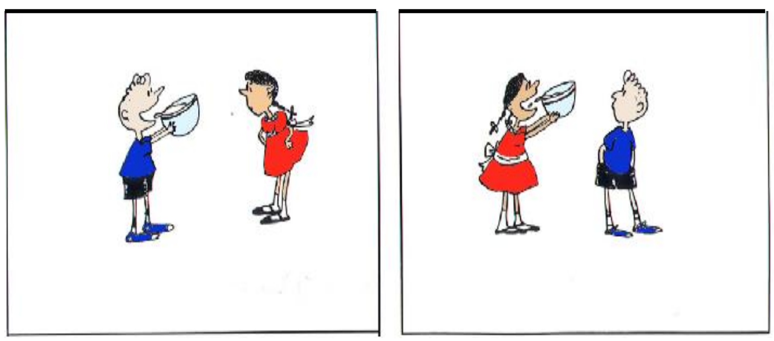
Number of Distinctions: 1
Answer: Left

4. The girl with the brown hair and pink clothes was being followed by the little boy holding the toy truck.



Number of Distinctions: 1
Answer: Right

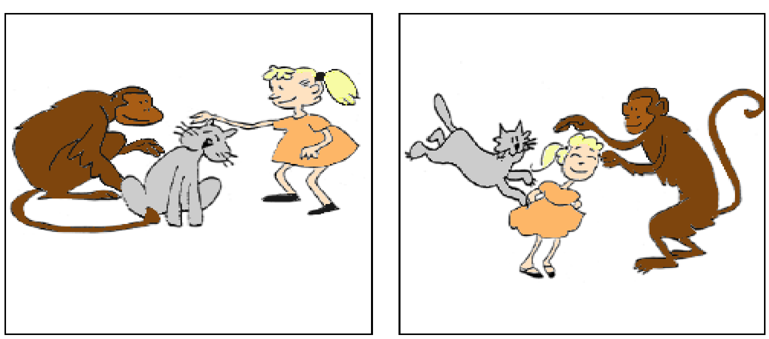
5. The boy in the black shorts drinking milk from the bowl was watched by the girl wearing the red dress.



Number of Distinctions: 1
Answer: Left

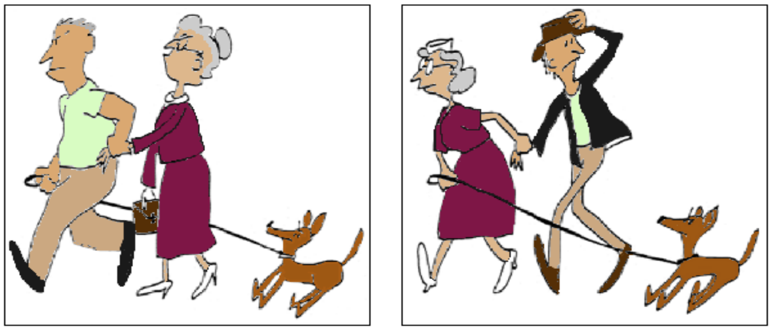
Active Conjoined Sentences

6. The girl in the orange dress is looking at the monkey and petting the grey cat sitting next to him.



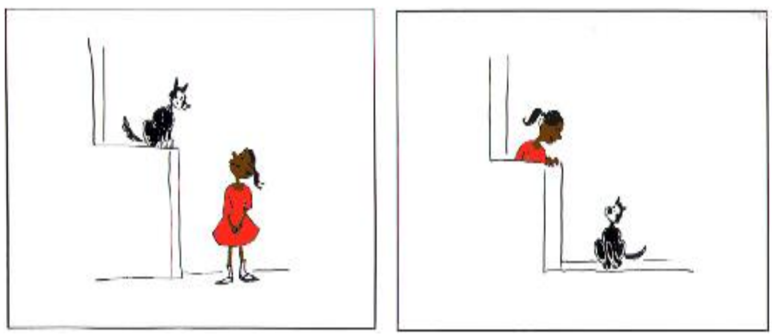
Number of Distinctions: 2
Answer: Left

7. The woman with glasses is pulling the worried man in the hat and pulling the brown dog on a leash.



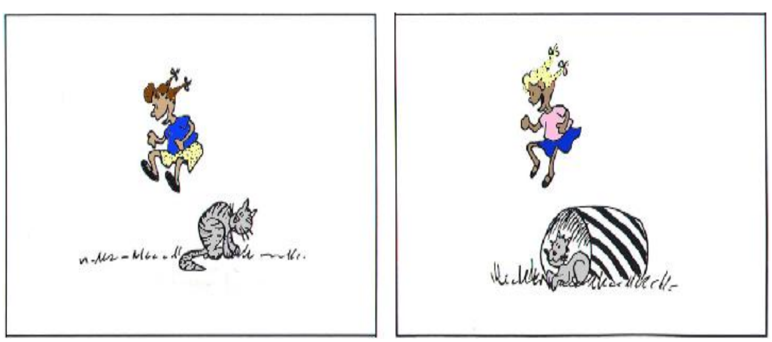
Number of Distinctions: 2
Answer: Right

8. The cat with black fur sat on the step and looked down at the little girl wearing a red dress.



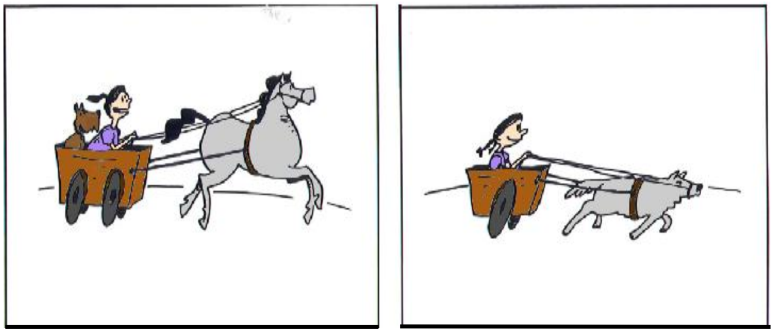
Number of Distinctions: 2
Answer: Left

9. The girl with two braids is wearing a blue skirt and jumping over the grey cat sitting on the ground.



Number of Distinctions: 1
Answer: Right

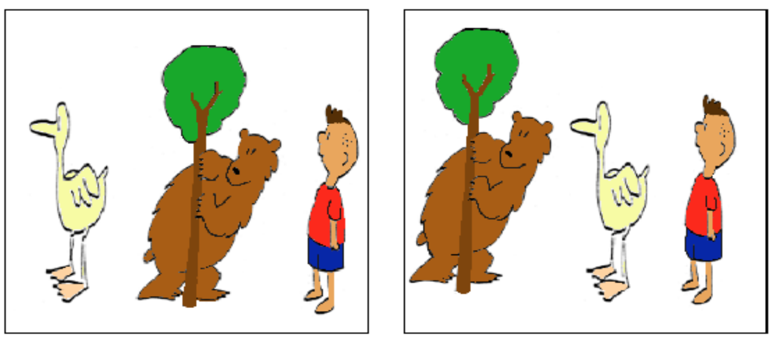
10. The girl with dark hair is steering a chariot and she is sitting in the one with a single wheel.



Number of Distinctions: 1
Answer: Right

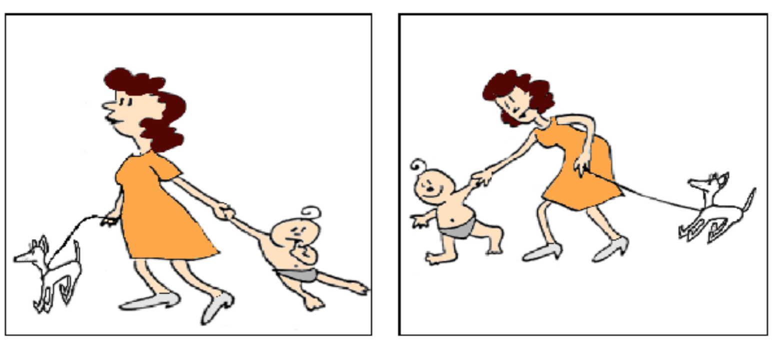
Sentences with Subject-Relative Center-Embedded Clause

11. The bear peeking out from behind the tree who was being watched by the young boy was watching the duck.



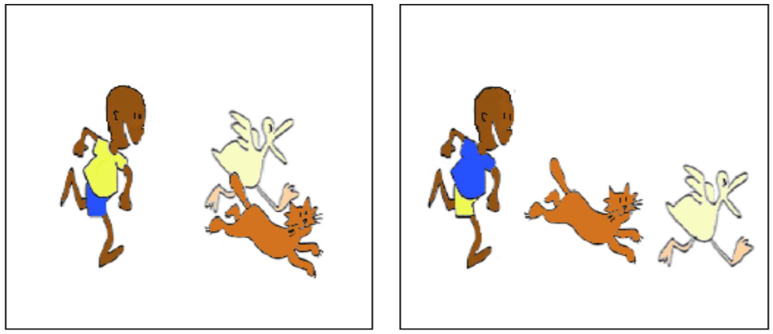
Number of Distinctions: 2
Answer: Left

12. The mother in the orange dress who was being pulled by the baby was pulling the dog on the leash.



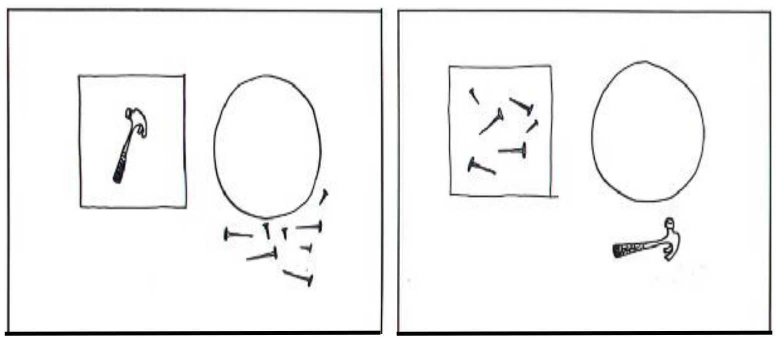
Number of Distinctions: 2
Answer: Right

13. The boy wearing a yellow shirt and blue shorts who was chasing the duck was also running after the cat.



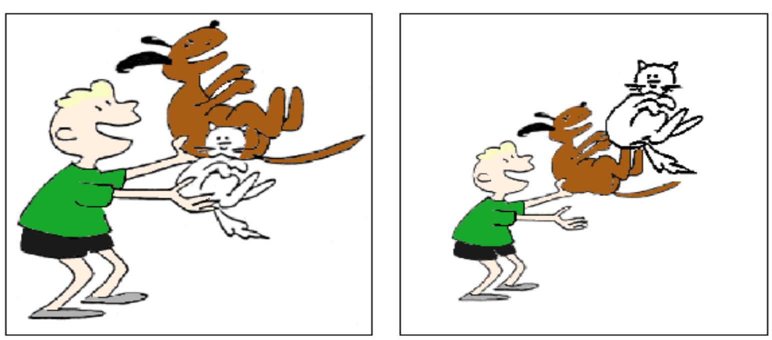
Number of Distinctions: 3
Answer: Left

14. The small black and white hammer that was used on the nails in the square was placed outside the circle.



Number of Distinctions: 2
Answer: Right

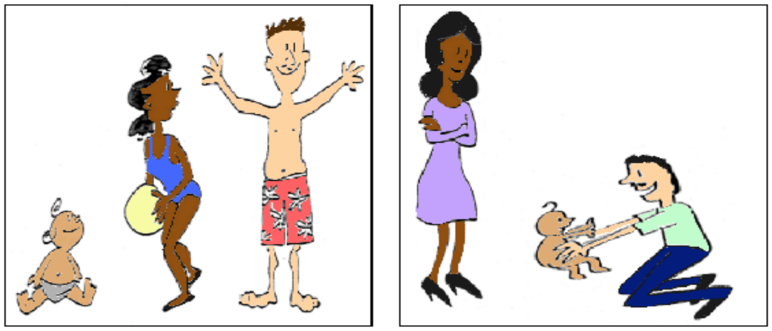
15. The brown dog that was carrying the white cat was being carried by the young boy in the green shirt.



Number of Distinctions: 2
Answer: Right

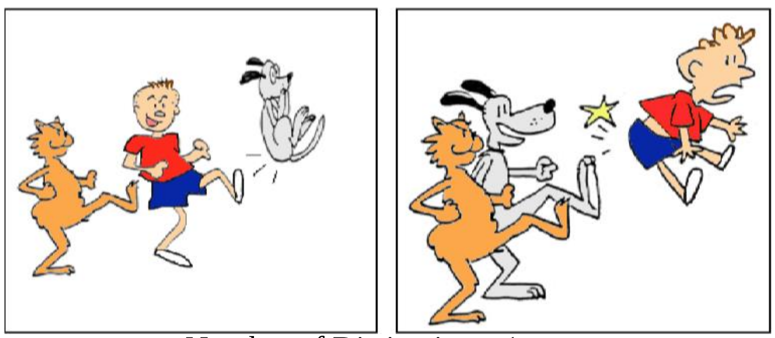
Sentences with Object-Relative Center-Embedded Clause

16. The mother with the black hair who the baby was watching was watching the father who has the short hair.



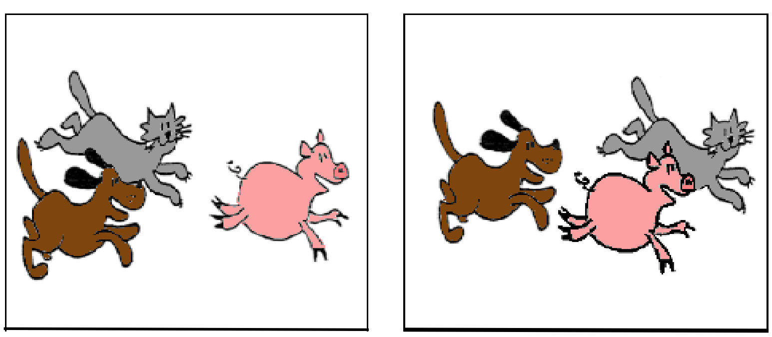
Number of Distinctions: 2
Answer: Left

17. The boy in the red shirt who the orange cat kicked was kicked by the grey dog with black ears.



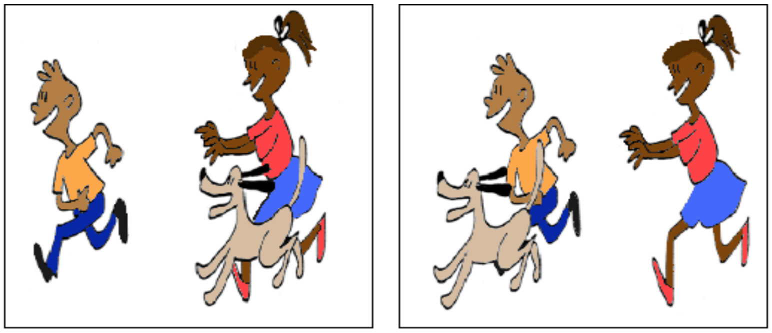
Number of Distinctions: 1
Answer: Right

18. The brown dog with the black ears that the pig was running away from was chasing after the grey cat.



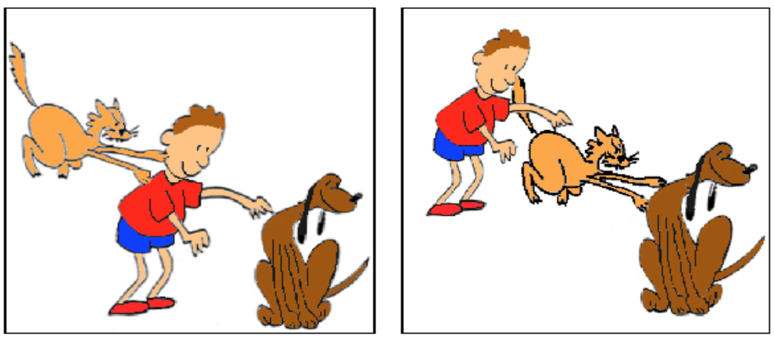
Number of Distinctions: 1
Answer: Right

19. The little boy who the girl with the ponytail chased was running away from the dog with the black ears.



Number of Distinctions: 1
Answer: Left

20. The boy in the red shirt who the orange cat had scratched was scratching the brown dog sitting behind him.



Number of Distinctions: 2
Answer: Left

References

Banai, K., Hornickel, J., Skoe, E., Nicol, T., Zecker, S., & Kraus, N. (2009). Reading and subcortical auditory function. *Cerebral Cortex*, *19*(11), 2699–2707.

Banoub, M., Tetzlaff, J. E., & Schubert, A. (2003). Pharmacologic and physiologic influences affecting sensory evoked potentials: implications for perioperative monitoring. *Anesthesiology*, *99*(3), 716-737.

Boersma, P. & Weenink, D. (2018). Praat: doing phonetics by computer [Computer program]. Version 6.0.44, retrieved from http://www.praat.org/.

Brown, J. A., Fishco, V. V., & Hanna, G. (1993). *Nelson-Denny reading test: Manual for scoring and interpretation, forms G & H.* Riverside Publishing.

Dobie, R. A. & Van Hemel, S. B. (Eds.) (2004). *Hearing Loss: Determining Eligibility for Social Security Benefits*. National Academies Press.

Friederici, A.D. (2002). Towards a neural basis of auditory sentence processing. *Trends in Cognitive Sciences*, *6*(2), 78–84.

Fallon, M., Peelle, J. E., & Wingfield, A. (2006). Spoken sentence processing in young and older adults modulated by task demands: Evidence from self-paced listening. *Journals of Gerontology - Series B Psychological Sciences and Social Sciences*, *61*(1), 10–17.

Gray, L. (2000). Auditory System: Structure and Function. Byrne, J. H. (Ed.), *Neuroscience Online.* Retrieved from https://nba.uth.tmc.edu/neuroscience/m/s2/chapter12.html.

Haught, P. A. & Walls, R. T. (2002). Adult learners: New norms on the Nelson-Denny reading test for healthcare professionals. *Reading Psychology, 23*(3), 217-238.

IBM Corp. Released 2017. IBM SPSS Statistics for Macintosh, Version 25.0. IBM Corp.

Kempler, D. (1996). *Kempler Sentence Comprehension Task.* David Kempler. Retrieved from http://word.emerson.edu/daniel_kempler/kempler-sentence-comprehension-testt/.

Kempler, D. & Van Lancker Sidis, D. (1996). *Formulaic and Novel Language Comprehension Test.* David Kempler. Retrieved from http://word.emerson.edu/daniel_kempler/familiar-and-novel-language-comprehension-test/.

Kidd, E., Donnelly, S., Christiansen, M. H. (2018). Individual Differences in Language Acquisition and Processing. *Trend in Cognitive Science, 22(*2), 154-169.

Mack, J. E., Meltzer-Asscher, A., Barbieri, E., & Thompson, C. K. (2013). Neural correlates of processing passive sentences. *Brain Sciences*, *3*(3), 1198–1214.

Neef, N. E., Schaadt, G., & Friederici, A.D. (2017). Auditory brainstem responses to stop consonants predict literacy. *Clinical Neurophysiology 128*(3), 484-494.

Nelson-Denny Reading Test Practice Questions. North Carolina Wildlife Resources Commission. Retrieved from https://www.ncwildlife.org/Portals/0/Careers/Documents/NelsonDenny_Study_Guide.pdf.

Peirce, J. W., Gray, J. R., Simpson, S., MacAskill, M. R., Höchenberger, R., Sogo, H., Kastman, E., & Lindeløv, J. (2019). PsychoPy2: experiments in behavior made easy. *Behavior Research Methods.* 10.3758/s13428-018-01193-y.

Pinel, J. P. J. (2000). *Biopsychology* (4th ed.). Boston: Allyn and Bacon. Retrieved from https://www.researchgate.net/figure/A-diagram-showing-the-classical-perisylvian-language-areas-Brocas-and-Wernickes-areas_fig2_37986949.

Pujol, R. & Irving, S. (2016). *Auditory Brain*. Journey Into the World of Hearing. Retrieved from http://www.cochlea.eu/en/auditory-brain.

Ramos, J.A., Kristensen S. G. B., & Beck D. L. (2013). An overview of OAEs and normative data for DPOAEs. *Hearing Review*, *20*(11), 30-33.

Rogalsky, C., Almeida, D., Sprouse, J., & Hickok, G. (2015). Sentence processing selectivity in Broca's area: evident for structure but not syntactic movement. *Language, Cognition, and Neuroscience, 30*(10), 1326-1338.

Skoe, E., Brody, L., & Theodore, R. M. (2017). Reading ability reflects individual differences in auditory brainstem function, even into adulthood. *Brain and Language*, *164*, 25–31.

Skoe, E., Krizman, J., Anderson, S., & Kraus, N. (2015). Stability and plasticity of auditory brainstem function across the lifespan. *Cerebral Cortex*, *25*(6), 1415–1426.

Skoe, E., Nicol, T., & Kraus, N. (2011). Cross-phaseogram: Objective neural index of speech sound differentiation. *Journal of Neuroscience Methods*, *196*(2), 308–317.

Tecoulesco, L. (2018). *Auditory brainstem response and language in typically developing children and children with Autism Spectrum Disorder* (Master's thesis, University of Connecticut).

Tecoulesco, L., Skoe, E., & Naigles, L. (in press). Phonetic Discrimination Mediates the Relationship between Auditory Brainstem Response Stability and Syntactic Performance. *Brain & Language.*